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High Frequency Radar Detection of Coronal Mass Ejections

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Abstract. Coronal mass ejections are now recognized to be one of the main causes of disruptive geomagnetic storms at the Earth. The detection of coronal mass ejections that are directed at the Earth therefore would be a signficant step in space weather forecasting ability. Currently, such ejections are detectable with coronagraph imaging primarily as solar limb events; thus the ejections are mostly directed away from the Earth. High frequency radars of sufficient effective radiated power are now becoming available that can directly detect Earthward-directed coronal mass ejections. Solar atmosphere sounding experiments in the early 1960s demonstrated this capability. It should be possible to reflect radar signals from the electron density enhancements in coronal mass ejections using high power radars in the 10 to 80 MHz range. The reflected signal will have a Doppler shift resulting from the Earthward-directed velocity of the coronal mass ejection. This measurement will provide an estimated travel time to the Earth of possible geomagnetic disturbances.

1. Introduction

Solar wind disturbances are known to cause significant perturbations in the Earth's magnetosphere that eventually are propagated into the ionosphere and manifest themselves in auroral displays, enhanced electrojets, and magnetic field variations. These perturbations can have undesired effects on such global systems as communications, electric power grids, and military and commercial satellites. Coronal mass ejections (CMEs) are now known to be one of the major drivers of large geomagnetic storms (Gosling 1993). Detection of these events with coronagraphs has provided one possible means of forecasting the occurrence on Earth of geomagnetic disturbances a few days hence. Existing and planned coronagraph measurements will be able to detect and track the movement of CMEs as far as 30 solar radii (R_o) from the Sun. Eventually, modeling may be able to forecast the evolution and development of CMEs similar to the way hurricane movements are forecast by tropospheric weather services. Coronagraph images provide information on the motion of CMEs transverse to the line of sight. It is more difficult for coronagraphs to detect the movement along the line of sight because of the presence of the (occulted) solar disk in the center of the field of view. Thus the total speed and direction of CMEs are not known initially, and Earthward-directed CMEs are difficult to resolve until they are detected by spacecraft closer to Earth. The Earthward-directed velocity can be detected with sufficiently powerful ground-based high frequency (HF) radars

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that transmit toward the Sun at frequencies above the ionospheric cutoff of the Earth but below peak coronal plasma frequencies. Typically, this range is from about 10 to 80 MHz for the solar radial distances of 1 to 5 R_o. The radio waves reflected from density enhancements in the leading edge of the CME will be detected with a positive Doppler shift in the 10s of kHz range, depending on the speed of Earthward-directed motion. Combined with the coronagraph measurements of the transverse velocity in the same range of radial distances, the total velocity of a CME could be determined and an evaluation made of the possibility of ensuing geomagnetic disturbance at Earth a few days hence. Several existing and planned radar facilities are capable of conducting tests of this CME radar detection technique.

2. HF Radar Diagnostics

The use of HF radars for detecting solar activity is not a new concept. Radar tests were conducted in the 1959-64 time period with a relatively low power (~500 kilowatts) array of HF dipoles designed to "sound" the solar atmosphere. A comprehensive review of the early tests is given by James (1968). The early tests successfully detected reflected radio waves and provided some initial diagnosis of the coronal plasma. The observed Doppler shifts in the return signal were typically in the range of ±15 kHz and were associated with the solar wind motion of the coronal plasma and with plasma turbulence. The observations were made during the declining phase of solar cycle 19. More recent studies with ground-based and space-based visible light coronagraphs (Howard et al. 1985, 1986; Sheeley et al. 1986; Hundhausen 1994) show that CMEs are more likely during the active phases of the solar cycle; thus the early radar tests were done during years relatively favorable for coronal mass ejections. However, the published data do not show frequency shifts that might clearly be associated with a coronal mass ejection. Several factors may have prevented detection of CMEs in the early tests: coronal mass ejections were unknown as distinct solar events in the early 1960s, so there was no impetus to search specifically for such events; it is possible that the integration times required to get good signal-to-noise ratios in the early experiments also prevented distinct CME events from being identified; and the HF array could not be steered to track the Sun and had to make its measurements in transit mode, which allowed only about one-half hour per day for actual transmission and reception. In spite of these limitations, enough data were collected to derive a radar cross section for the Sun of about 1°, which was associated with the reflecting size of the corona.

At about the time of the early solar radar tests, similar experiments in diagnostics of the Earth's ionosphere were beginning. Reviews of the use of incoherent scatter radars for ionospheric diagnostics are provided by Evans (1969) and by Farley (1971). Incoherent scatter radars are now used routinely to detect ionospheric density irregularities and motions at several sites around the world. Although designated as "incoherent," the scattering cross section is actually determined by collective plasma effects associated with the Debye electron cloud shielding the ions.

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In addition to incoherent scatter radars, ionospheric experiments have also included so-called "heating" radars, in which high power HF radiowaves are used to increase the electron temperature at localized altitudes illuminated by the radar. These experiments transmit at a frequency that matches the electron plasma frequency at the critical density altitude. The critical electron density is related to the electron plasma frequency by the formula $f_p = 9\sqrt{N_e}$, where N_e is the electron density in electrons cm^{-3} and f_p is the plasma frequency in kHz. In a typical ionospheric experiment, a heating frequency of 5.1 MHz corresponds to a electron density of 3.2 x 10^5 electrons cm^{-3} at an altitude of about 300 km. Among other interactions, reflection and absorption of the HF waves at the critical density altitude occur in these experiments. A discussion of wave-plasma interactions caused by heating radars can be found in the book by Gurevich (1978).

3. Expected HF Signature of Coronal Mass Ejections

Coronal electron densities as a function of solar radii are available from several sources. In Fig. 1 we plot several electron density profiles. These are the Baumbach-Allen model (Allen 1973), an extrapolation of HELIOS power law models based on spacecraft observations between 1.0 and 0.3 AU (Marsch 1991, and references therein), and a combination of the preceding two models. Other measurements based on radio scintillations are generally consistent with the profiles shown in Fig. 1.

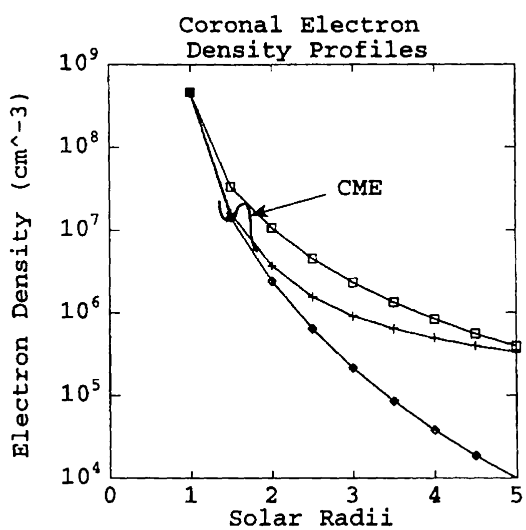

Figure 1. Model electron density profiles of the solar corona for 1 to 5 solar radii. A schematic density enhancement of a CME is shown.

The electron plasma frequency profiles based on the electron density models are shown in Fig. 2. Over the range of 1 to 5 solar radii, the electron plasma frequency varies from about 80 to 10 MHz, defining the range of HF frequencies

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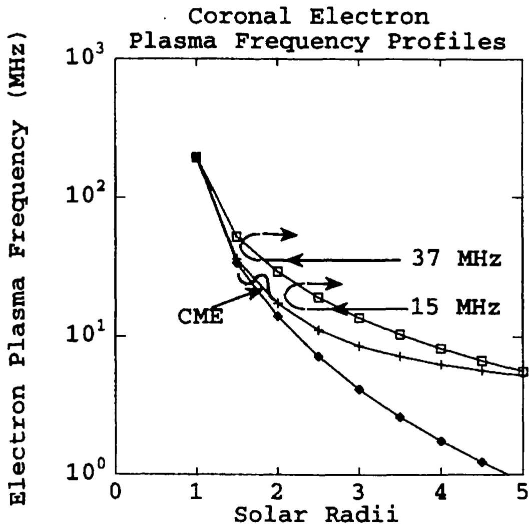

Figure 2. Electron plasma frequency profiles in the solar corona. HF rays at 15 and 37 MHz are shown as reflecting from critical plasma frequencies at about 2.0 and 1.5 solar radii, respectively.

that Earth-based radars would use to reflect from the solar corona. The peak frequency in the F2 region of the Earth's noontime ionosphere defines the low frequency cutoff for transmission from the Earth to the Sun. This value is typically at about 9 MHz, corresponding to a peak electron density of 10^6 electrons cm^{-3} in the Earth's ionosphere. We illustrate the propagation of HF waves into the solar corona at 15 and 37 MHz by the lines indicating reflection at distances of about 2 and 1.5 solar radii, respectively, where the corresponding coronal critical plasma densities are reached. The range of solar radii shown matches closely the range of radial distances for existing coronagraph images, which have provided the data base of ejection velocities and geometric sizes of CMEs. Thus, in the future, the HF radar experiments would be able to use correlative coronagraph images in the analysis of the HF measurements. Various interpretations of coronagraph images suggest that the white light scattered from CMEs is caused by Thomson scattering from enhanced electron densities. Although coronagraph images column-integrate the light intensity, it is expected that the majority of the enhancement is localized in the region of the CME. Behind the white-light enhancement, there is often a darker region, suggesting a reduction of electron densities below normal background levels. In general, white light images thus suggest that the leading edge and the sides of the CME are often associated with density profiles similar to the sketch in Fig. 1.

In the smoothly varying model profile, the leading edge electron density enhancement and backside electron depletion of the CME provide a distinctive signature for detection by reflection of HF radiowaves. A frequency corresponding to a critical density of the leading edge would be returned with phase delay

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shorter than a second, higher, frequency that reflects at a critical density closer to the Sun. Such a phase delay relationship would be observed to evolve during the outward motion of the CME, which can be about one hour for the radial distances shown.

Coronagraph images have provided a distribution of velocities by measurement of the displacement of the leading edge in successive CME images. Because only the transverse velocity is detected in successive displacements, the apparent radial velocities may include a component in the line of sight, either toward or away from the Earth, that cannot be detected. From the relatively large number ($\sim$1000) of distinct CMEs observed with coronagraphs however, the distribution of Earthward velocities is undoubtedly close to the distribution of transverse velocities. The velocities range from as low as 100 km s^{-1} to above 1500 km s^{-1}. For this range of Earthward-directed velocities and using 15 and 37 MHz as typical HF frequencies, the expected range of Doppler shifts is shown in Fig. 3.

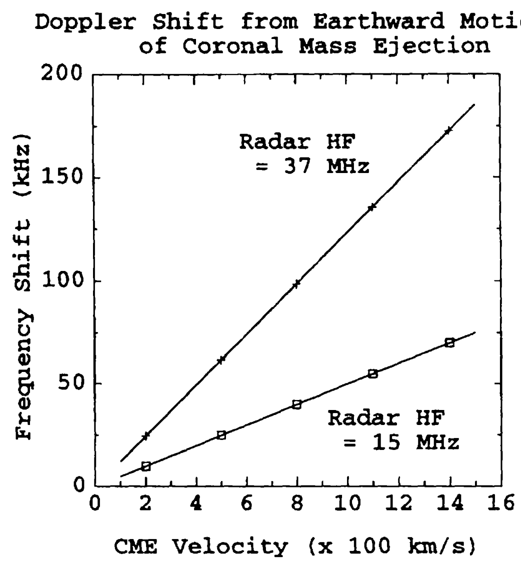

Figure 3. The Doppler shifts expected for HF frequencies of 15 and 37 MHz, for the range of CME velocities observed by coronagraphs.

A schematic illustration of the reflection of HF radiowaves from the leading surface of an Earthward-directed CME is shown in Fig. 4. In this sketch, the CME is shown as a structure with a size similar to that of the Sun and illustrates that CMEs are very large scale disruptions of the solar corona. For some CMEs, coronagraph images suggest that the leading edge departs from a quasi-spherical geometry and becomes flattened or even slightly concave in the outward radial direction. The flat or concave surfaces have been associated with slow and intermediate shock fronts in the leading edge of the CME (Steinolfson & Hundhausen 1990). Plasma density jumps in the modeled shock surfaces may provide a reflecting surface for the HF radiowaves. The flattening of the CME leading edge would also be favorable for enhanced reflection of HF power back toward Earth when the CME is Earthward directed. The flattened surface thus

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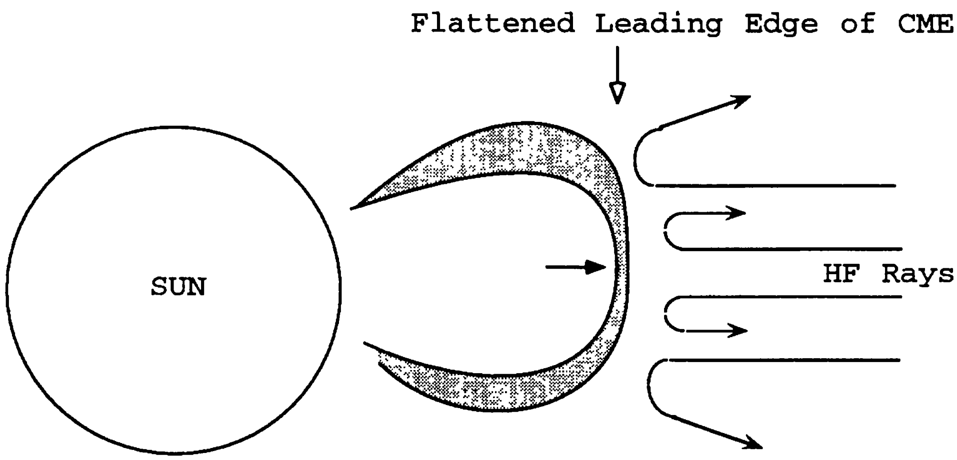

Figure 4. Schematic diagram of HF rays launched from Earth and reflecting from the leading edge of an Earthward-directed CME. The flattened leading surface provides a favorable geometry for enhanced power return to Earth.

resembles a "moving mirror" for HF waves, with fewer HF rays being refracted away from the radial direction.

4. Departures from Smooth Density Profiles

Spacecraft solar wind data show considerable structure and variability in plasma densities, associated with high and low speed solar wind streams, interplanetary shocks, and CMEs. The structure in the solar wind has been measured by the HELIOS spacecraft to 0.3 AU ($\sim$65 R_o), and the large scale structure is thought to map back to the solar corona. The solar corona can thus be expected to have both spatial and temporal variations which the model profiles in Fig. 1 do not show. An actual experiment with solar radars to detect coronal mass ejections will likely have spreads in both Doppler shift and phase delay due to fluctuations in the coronal plasma. The early solar radar tests clearly show this effect. CME detection must therefore be done with careful analysis of the data for distinct signatures. Higher effective radiated power and increased senstivity will obviously help, and modern HF radars may provide both of these attributes compared with the early tests.

Increasing solar activity will result in increasing solar radio bursts that would be detected by ground-based receiving antennas used for the CME experiments. It is clearly important that experiments be conducted while general solar activity is not so high that CME-reflected signatures might be hidden by naturally occurring solar noise in the HF spectrum. The transmitted HF signal must be encoded with a distinct pattern, and correlation techniques must be used to discriminate against the natural noise background. Greater transmitted HF power and/or receiving sensitivity than was available in the early tests will obviously be an advantage.

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5. Recent Related Tests

Several tests have recently been conducted that have attempted to demonstrate the feasibility of using HF radars for diagnosing the space environment. One test (Hildner 1995) has used the Department of Defense OTH-B radar to transmit radio waves toward the Sun in an attempt to detect the waves reflected from the solar corona. The data from the recent tests with the OTH-B are now being analyzed, and results are not yet available. The OTH-B radar is more powerful (6 MW) than the early tests, and it is thus expected that the reflected waves will be detected.

Very recently, the SURA radar facility in Russia has been used to transmit test signals to the WIND satellite in orbit about the Earth (Kaiser 1995). The WIND satellite has an apogee of about 70 Earth radii in the upstream solar wind, where it is being used to detect solar wind disturbances about 20 minutes before they arrive at Earth. The SURA radar (20 MW) beamed signals at about 9 MHz to WIND, where they were received by the Radio and Plasma Waves experiment (WAVES) aboard WIND. These tests have demonstrated the use of ground-based HF radars to transmit to distant regions of the solar wind.

The use of other facilities, such as Arecibo, Jicamarca, and the new HF Active Auroral Research Program (HAARP) radars, may allow several frequencies and diagnostics approaches to be used to detect CMEs. Each of these facilities has or will have certain advantages that can be exploited. For example, the HAARP radar is planned to be steerable through the use of electronic phasing of the transmitting dipoles (HAARP Executive Summary 1995), with a final planned effective radiated power of about 1 GW. Combined radar operations will also be possible, such as the use of HAARP and SURA to provide wider daily coverage during periods of potential coronal mass ejections.

6. Conclusions

The new solar cycle 23 is currently beginning and is expected to peak in about the year 2000. Increasing solar activity is expected to produce an increased rate of coronal mass ejections. Thus the time is optimum for proof-of-principal experiments in detecting Earthward-directed CMEs with high power HF radars. The development of experimental techniques and plans should begin now. Modifications to some existing radar facilities may be necessary and possible in order to be ready for tests in the near future. Coordination with space coronagraph experiments, such as the Solar and Heliospheric Observatory (SOHO) experiment, is also possible. The results of these research efforts will be incorporated into newly developing models of magnetosphere-ionosphere global dynamics and the response of this system to solar disturbances. Several models in current use by both military and civilian sectors to forecast geomagnetic disturbances will benefit by this research.

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Group Discussion

Webb: A very intriguing talk. I have one problem. As we know, brighter and faster CMEs tend to drive shocks ahead of them. The shocks can have bright dense regions which are turbulent. What would this region do to the Doppler signal you are trying to measure?

Rodriguez: Using observations in interplanetary shocks and the Earth's bow shock as a guide, the spectrum of wave turbulence may be mostly of low frequencies, associated with ion sound waves. These would have a broadening effect on the HF waves, but the largest shift would be due to the directed motion of the shock.

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Hildner: Webb asked: approximately, will the shock in front of a fast CME confuse the radar observations of a CME?
There exists a very strong radial gradient of n_e, whereas the density jump at a shock can be, at most, 4 times. The density behind the shock rises swiftly toward the Sun, so the altitude where the plasma frequency equals the radar's frequency will be close behind the shock anyway. Thus, even if the density jump at the shock has some confusing effect on the radar observations, it will not seriously deteriorate measurements of CMEs.

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